Draft version February 2, 2008
Preprint typeset using LaTeX style emulateapj v. 7/15/03

QUANTIFYING THE DRIVERS OF STAR FORMATION ON GALACTIC SCALES. I. THE SMALL MAGELLANIC CLOUD

Dennis Zaritsky
Steward Observatory, University of Arizona, 933 N. Cherry Ave., Tucson, AZ 85721, USA; dzaritsky@as.arizona.edu

Jason Harris*
Space Telescope Science Institute, 3700 San Martin Dr., Baltimore, MD, 21218, USA

Draft version February 2, 2008

ABSTRACT

We use the star formation history of the Small Magellanic Cloud (SMC) to place quantitative limits on the effect of tidal interactions and gas infall on the star formation and chemical enrichment history of the SMC. The coincident timing of two recent (< 4 Gyr) increases in the star formation rate and SMC/Milky Way(MW) pericenter passages suggests that global star formation in the SMC is driven at least in part by tidal forces due to the MW. The Large Magellanic Cloud (LMC) is the other potential driver of star formation, but is only near the SMC during the most recent burst. The poorly constrained LMC-SMC orbit is our principal uncertainty. To explore the correspondence between bursts and MW pericenter passages further, we model star formation in the SMC using a combination of continuous and tidally-triggered star formation. The behavior of the tidally-triggered mode is a strong inverse function of the SMC-MW separation (preferred behavior $\sim r^{-5}$, resulting in a factor of ~ 100 difference in the rate of tidally-triggered star formation at pericenter and apocenter). Despite the success of these closed-box evolutionary models in reproducing the recent SMC star formation history and current chemical abundance, they have some systematic shortcomings that are remedied by postulating that a sizable infall event ($\sim 50\%$ of the total gas mass) occurred ~ 4 Gyr ago. Regardless of whether this infall event is included, the fraction of stars in the SMC that formed via a tidally triggered mode is $> 10\%$ and could be as large as 70%.

Subject headings: galaxies: evolution — galaxies: interactions — Magellanic Clouds

1. INTRODUCTION

Galaxy evolution is sufficiently complex and the processes that drive star formation sufficiently unknown that current state-of-the-art models must resort to simple parameterizations of the physics involved (see Kauffmann et al. (1993); Cole et al. (1994); Somerville & Primack (1999)). Fits of these models to global averages such as the galaxy luminosity function or volume averaged star formation as a function of lookback time (the "Madau" plot; Madau et al. (1998)) provide weak constraints on important details buried well within the models. With the nearly unlimited freedom in the parameterization of galaxy interactions and the effects of these interactions on the star formation history of galaxies, the experiments as currently practiced primarily provide consistency checks that are reassuring but not definitive. Progress in this field requires external, empirical, quantitative constraints on how star formation is driven by interactions and infall.

Local Group (LG) galaxies are the only galaxies for which current observations can resolve sufficiently faint stars, red giant branch or fainter, with which one can constrain both the recent and ancient star formation history (SFH). The availability of the entire SFH enables us to identify and quantify the factors that have influenced the star formation rate (SFR) over time. Even among LG galaxies, such work remains quite difficult beyond the sphere of influence of the Milky Way (MW) because color-magnitude diagrams (CMDs) do not reach stars below the horizontal branch across the entire face of a galaxy. Within the accessible volume there are a number of interesting stellar systems and various studies have already illustrated the rich taxonomy of SFHs (for a review see Mateo (1998)). The two most massive systems (excluding the MW for which study is complicated by our position within it) are the Large and Small Magellanic Clouds (LMC and SMC). These satellite galaxies are qualitatively different than the remainder of the sample because they currently contain large gas reservoirs and continue to vigorously form stars. Of the systems we can study in detail and in their entirety, these are the most similar to galaxies observed outside the Local Group.

In addition to its fortuitous placement, the Small Magellanic Cloud has another characteristic that makes it suitable for this study. Because it has no spiral structure and is unbarred (Zaritsky et al. 2000), it has no apparent internal mechanism that can drive global modes of star formation. More massive galaxies, like the LMC which has both bars and spiral arms, are more complex. Unfortunately, the SMC's low mass makes it susceptible to losing substantial amounts of gas during its evolution. Its velocity dispersion is sufficiently low (25.3 km sec^{-1} measured from planetary nebulae (Dopita et al. 1985) and 27 km sec^{-1} from C stars (Hardy et al. 1989)) that gas outflow during vigorous phases of star formation is expected (Martin 1999; Garnett 2002). Although we want to understand global star formation in both more and less massive systems, the more massive ones will be com-

*Current address: Steward Observatory, University of Arizona, 933 N Cherry Ave., Tucson, AZ, 85721, USA; jharris@as.arizona.edu

plicated, perhaps dominated, by internal drivers of star formation such as local instabilities (Spitzer 1968; Quirk 1972; Kennicutt 1998) and the less massive ones will be even more susceptible to outflow. The SMC may be a good initial object for study.

The star formation history of the SMC (Harris & Zaritsky 2003) has several distinctive features that should provide leverage on constraining simple evolutionary models. We address the following questions: 1) by what factor is star formation increased during tidal interactions, 2) what fraction of the stars formed during those tidal interactions, 3) does a closed-box model satisfactorily reproduce the data, and 4) if infall or outflow is required, what are its effects and how much is necessary? In §2 we provide a brief description of the data and refer readers to Zaritsky et al. (2002) and Harris & Zaritsky (2003) for more details. In §3 we describe the models and discuss our fitting of these models to the SFH of the SMC. We summarize and conclude in §4.

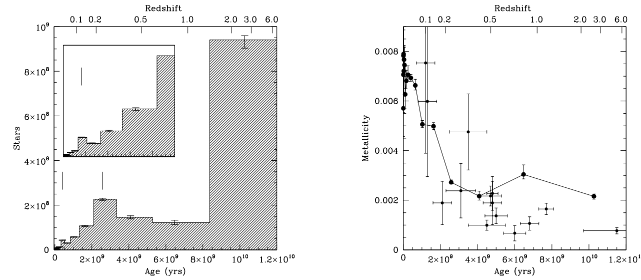

Fig. 1.— Reprise of the results from Harris & Zaritsky (2003). The left panel shows the stellar age function (SAF) for the entire SMC, while the right panel shows the chemical enrichment history. Age = 0 corresponds to the current day. The histogram is used only to highlight the shape of the SAF, the height rather than the integral of each bin represents the number of stars of that age. Unconnected circles in the right panel represent the ages and metallicities of individual clusters de Freitas Pacheco et al. (1998); Piatti et al. (2001). The connected circles represent the results from the field star analysis of Harris & Zaritsky (2003). The inset in the left panel is a magnification of the plot at young ages. The conversion from age to redshift in this Figure and throughout the paper is done for the WMAP cosmology (Spergel et al. 2003).

2. THE DATA

The original data come from the Magellanic Clouds Photometric Survey and are presented and made public by Zaritsky et al. (2002). They consist of UBVI photometry of over 5 million stars in the central $4° \times 4.5°$ area of the Small Magellanic Cloud. The reconstruction of the star formation history was done by Harris & Zaritsky (2003) using the StarFISH algorithm presented and made public by Harris & Zaritsky (2001).

We reprise the recovered star formation and chemical enrichment history in Figure 1. Instead of plotting the star formation rate as a function of time, which when plotted in age bins of different widths can be visually misleading if the SFH is bursty, we plot the number of stars of each age. We refer to this quantity as the stellar age function (SAF). The data necessary to produce the more standard average SFR plot is presented by Harris & Zaritsky (2003).

We combine the data from all of the spatial bins described by Harris & Zaritsky (2003) and propagate the internal errors quoted there to arrive at the global SAF. Before discussing the SAF, we note that the oldest bin represents all stars older than ~ 8 Gyr. Therefore, although the SAF is well defined for ages > 8 Gyr, the SFR is not. From the left panel of Figure 1 we draw two key conclusions regarding the SAF: (1) there are two statistically significant upward deviations from the general declining nature of the function with time at ~ 0.4 and 2.5 Gyr and (2) there is clear drop in the SAF from the oldest bin to the next oldest (for a constant star formation rate, the SAF in the ~ 5 to 8 Gyr bin would be greater than that in the ~ 3.5 to 5 Gyr bin by 50%). The apparent deficit in the inferred SFR at intermediate ages cannot be explained away by extending the width of the bin representing the oldest stars back in time (see discussion below).

The right panel of Figure 1 also contains two intriguing, but less statistically significant, results regarding the chemical enrichment: (1) we derive a chemical enrichment history for field stars from an analysis of broad-band stellar photometry that agrees with that from the analyses of individual stellar clusters (de Freitas Pacheco et al. 1998; Piatti et al. 2001), and (2) the chemical abundance is either constant until ~ 3 Gyr ago or has a slight decline after ~ 6 Gyr ago. The latter result is at a fairly low confidence level from our data alone due to the use of broad-band colors, but consistent with the cluster data. Because we consider of the uncertainties we will not fit our models to the chemical enrichment history, but we will compare the chemical enrichment history predicted by the models to the observations.

3. THE MODELS

We begin our attempts to reproduce the observations with a simple, closed-box model galaxy evolution model. The galaxy initially consists of a certain mass of gas. It converts that gas to stars at a rate proportional to the current gas mass until the gas is exhausted. This simple parameterization is analogous to the disk star formation law proposed by Schmidt (1959), SFR $\propto \Sigma^n$ where Σ is the gas surface density and n is to be determined empirically. Schmidt (1959) found $n = 2$, but more recent work finds $n = 1.3 \pm 0.3$ when the gas density lies above a threshold value (Kennicutt 1989). Whether these results are directly applicable to a low-mass system like the SMC, which is not a simple tilted HI disk (Staveley-Smith et al. 1997). For simplicity, and out of ignorance, we have adopted a SFR $\propto M_g$, which results in an exponentially declining star formation history.

For the SMC, where we have both a measurement of the stellar mass, from our catalog, and the remaining gas mass, from the H I and cold dust measurements of Stanimirovic et al. (2000), the initial gas mass is observationally constrained to be the sum of these two masses for a closed-box model. We define the "quiescent" (Q) rate of star formation as the fraction of the available gas per Gyr that is converted to stars. The "tidally triggered" (TT) mode of star formation is modeled with a continually varying SFR that is inversely related to the distance between the SMC and MW and is specifically $A/(r/40\mathrm{kpc})^b$, where r is the distance between the SMC and MW in kpc, A is a normalization constant that sets

the relative efficiencies of the Q and TT modes, and b parameterizes the unknown physics that relates the tidal field to star formation. The model assumes complete instantaneous recycling of material with effective yield, y, which allows us to also predict the corresponding age-metallicity relation. We set the yield, 0.009, to reproduce the current chemical abundances. This value is within the range of effective yields determined for similar galaxies in previous studies (Vila-Costas & Edmunds 1992; Garnett 2002). We trace the orbit of the SMC for t_{AGE} Gyr and calculate the SFR along the orbit. To compare to the observational data, we calculate the SAF and stellar metallicity integrated over the same time bins defined by isochrone set used by Harris & Zaritsky (2003).

The available external constraints, such as the measurement of the remaining gas mass (Stanimirovic et al. 2000), the time of the pericenter passages, (Lin et al. 1995; van der Marel et al. 2002), and the current metallicity (Vila-Costas & Edmunds 1992; Garnett 2002), effectively limit many of the model parameters. The model has only two parameters, A and b, which are unconstrained by observations other than the SAF and age-metallicity relationship and which are somewhat degenerate because they both help determine the relative importance of the TT mode.

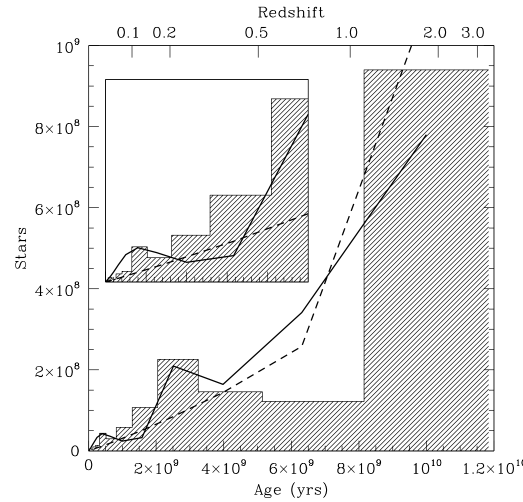

Fig. 2.— Comparison of a model with only quiescent-mode star formation (dashed line; Model 1 in Table 1), a model with tidally-triggered bursts (solid line; Model 2 in Table 1), and the measured SAF (histogram). The inset is an expanded version of the most recent 2.5 Gyr.

3.1. *Selecting the Model Parameters*

3.1.1. *Remaining and Initial Gas Masses*

In our closed-box model, the galaxy is initially composed entirely of gas, with mass equal to the sum of the present gaseous and stellar masses. From our photometry we have a measurement of the total number of stars, which is the sum of the SAF. For the amount of remaining, unused gas (neutral hydrogen plus molecular gas) we adopt the measurement provided by Stanimirovic et al. (2000) of $1.2\times10^9 M_\odot$. The molecular gas mass is highly uncertain, but in this current estimate it is about twice that of the H I. Our simple model does not differentiate between atomic and molecular gas. Constraining the initial gas mass fixes the integrated star formation efficiency because the model must produce the observed number of stars. Once we select the relative efficiencies of the Q and TT modes, the model iterates to identify the specific values of those efficiencies that produce a match to both the final total stellar mass and the remaining gas mass. For a typical model of the SMC the inferred efficiency of the Q mode is such that $\sim1\%$ of the remaining gas mass is converted to stars per Gyr.

3.1.2. *Age*

As we discussed previously, we have no empirical constraint on the extent of the oldest bin backward in time from our data alone. The choice of when the SMC begins to form stars sets the ratio of the number of stars in the oldest bin to the number in all the other bins. Selecting an older age for the SMC's initial star formation places relatively more stars in the oldest bin, exhausts more of the gas at early times, and decreases the number of stars in the younger bins. As we run various models for the SMC (see below), we find that we are driven to adopt older SMC ages in an attempt to explain the dramatic difference in the SAF between the oldest and second oldest bins. The age that we find provides a good fit for the SMC (17 Gyr, see below), exceeds the measurement of the age of the Universe from the WMAP satellite (13.7 $\pm$ 0.2 Gyr, Spergel et al. (2003)). Because the age of the SMC cannot exceed 13.7 Gyr, this discrepancy reflects the difficulty that the model has in producing a sufficient number of stars in the oldest bin. Given the uncertainties in determining the SAF at the oldest ages and the realization that the closed-box model is probably least applicable at early times when the SMC is forming, we do not stress or require fine agreement at these times, nor do we interpret the best-fit age literally. Alternatively we could artificially increase the SFR at early times and adopt the WMAP age. Other than in this respect, the selection of the initial age does not affect the models.

3.1.3. *Orbital Model*

For a model invoking a TT mode of star formation, the adopted orbit is critical because it determines the rate and relative severity of the pericenter passages. We model the SMC's orbit about the MW using a simple analytic function that captures the oscillatory nature of the radial behavior with a *sine* function and the slow decay due to dynamical friction with a linear decline with time. We fix the slope of the amplitude decline to obtain a qualitatively acceptable fit to the data presented in Figures 11 and 12 of Lin et al. (1995). The advantage of this simple description over a more realistic orbit derived by integrating the equations of motion through a Galactic potential is that the result of period and phase changes on the SAF can be easily explored. For a few cases, we compare the resulting SAF using the analytic approach to that from full orbit integrations and find no significant difference.

The success of the TT mode in reproducing features in the SAF is first demonstrated in Figure 2. We compare two models (Models 1 & 2), the first of which has zero

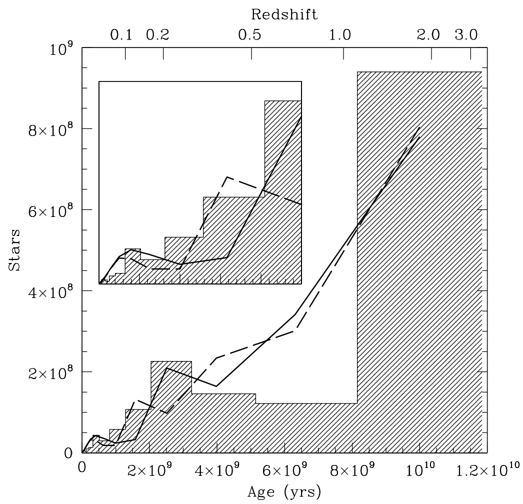

FIG. 3.— Comparison of the same tidally-triggered model as in Figure 2 (solid line; Model 2 in Table 1), a tidally-triggered burst model with an orbital period of 1.5 Gyr (dashed line; Model 3 in Table 1), and the measured SAF (histogram). The inset is an expanded version of the most recent 2.5 Gyr.

efficiency in the TT mode, the second of which has a TT amplitude interactively set to produce a good qualitative fit to the observed SF peaks at ~ 0.4 and 2.5 Gyr. Model parameters and reduced χ^2 values are given in Table 1. Model 2 demonstrates that a simple implementation of pericenter-driven star formation can reproduce the fluctuations observed in the SMC's recent ($t < 4$ Gyr) SAF. Model 1, with no TT mode, fails to reproduce the observed SAFs at the times of the two bursts by 27 and 35σ, while Model 2 fails by only 3.5 and 1.1σ. Although the TT mode is not a unique way to enhance the star formation at these two epochs, the improvement in reproducing the SAF is dramatic with even minimal tuning. We discuss the choice and sensitivity of the results to the orbital parameters next.

In this admittedly oversimplified model, the period and phase of the orbit directly determine the times at which bursts are observed. If there is no discernible lag between pericenter passage and increase in star formation, then the peaks in the SAF determine the orbital period and phase. Because we do not know whether tidally triggered star formation is expected to peak exactly at pericenter, the positions of the peaks do not yet place a strong constraint on the orbital phase. If we allow the period and phase of the orbit to vary so as to optimize the match, we find a best-fit period that is slightly longer than that given by Lin et al. (1995) or van der Marel et al. (2002) of 2.4 Gyr and a time since the most recent pericenter of 0.2 to 0.4 Gyr (depending slightly on other parameter choices). A comparison to a model with an orbital period of 1.5 Gyr (Model 3) is given in Figure 3 to demonstrate the sensitivity of the predicted SAF to the chosen period. The 1.5 Gyr period model fails because it does not reproduce the separation between the two peaks in the SAF.

Is our estimate of the orbital period in conflict with the constraints from proper motion studies? The most detailed recent study of the LMC proper motion comes from the study of van der Marel et al. (2002). If, as is generally seen in simulations (Gardiner et al. 1994), the SMC and LMC orbit the MW as a pair, then the parameters of the LMC orbit should be quite similar to those of the SMC. Determining the orbit of the LMC around the MW requires both a precise measurement of its present-day space velocity and an accurate model of the Galactic potential. We model the MW potential with a spherical isothermal dark halo of circular velocity 180 km sec^{-1} and an interior disk + spheroid mass of $1.5 \times 10^{11} M_\odot$. This model has an enclosed mass of $5 \times 10^{11} M_\odot$ at the current position of the LMC (50 kpc), which agrees with determinations of the enclosed mass at that position (Lin et al. 1995; Kochanek 1996), and an enclosed mass of $1.8 \times 10^{12} M_\odot$ at 230 kpc, which agrees with estimates of the enclosed mass at that radius (Zaritsky et al. 1989; Wilkinson & Evans 1999). In the most recent determination of the LMC proper motion, van der Marel et al. (2002) find that $v_{LMC,rad} = 84 \pm 7$ km s^{-1} and $v_{LMC,tan} = 281 \pm 41$ km s^{-1}. Using these values as the initial conditions of an orbit that is integrated backward in the adopted potential results in a time since pericenter passage of 0.09 Gyr and a period of 1.9 Gyr. However, the tangential velocity has a large uncertainty and increasing it by 1σ results in a time since pericenter passage of 0.06 Gyr and a period of 2.7 Gyr. Therefore, our estimated period of 2.4 Gyr is within a 1σ change in the tangential velocity.

The time since the most recent pericenter passage is less well constrained from the star formation modeling because we do not know whether the star formation maxima correspond precisely to pericenter passages. One can imagine models in which they either lag or lead the pericenter passage. Eventually, when the proper motions and Galactic potential are better determined and the orbital constraints are sufficiently tight, this type of analysis could determine at what phase in the orbit the star formation is maximized during an interaction. For now, we conclude that (1) the peaks are well reproduced given the published orbital parameters, and (2) the lack of peaks at ages > 4 Gyr is not a result of a lack of a rise in star formation at pericenter, but rather an artifact of the large binning made necessary by our poorer resolution for those times. The binning, not only the width but also the placement of the bins, is critical as is shown in Figure 4 where the model (Model 4), with an adopted time since last pericenter of 2.1 Gyr, lacks strong peaks even though it is otherwise exactly the same as Model 2. This comparison provides a cautionary note that one should not necessarily interpret smooth star formation histories as evidence against episodic star formation (see also Flint & Harris (2003)) and that one should strive for the highest temporal resolution possible when investigating triggered bursts. Our bins are determined by the isochrone set and degeneracies between certain ages given the quality of our data (see Harris & Zaritsky (2003) used to recover the SFH. The binning was chosen independent of any observed variations in the SAF. Given a precise model for the star formation history, one could create a CMD and compare directly to the data. This method would provide a more sensitive way to test details of the model, but a more difficult way to explore parameter space.

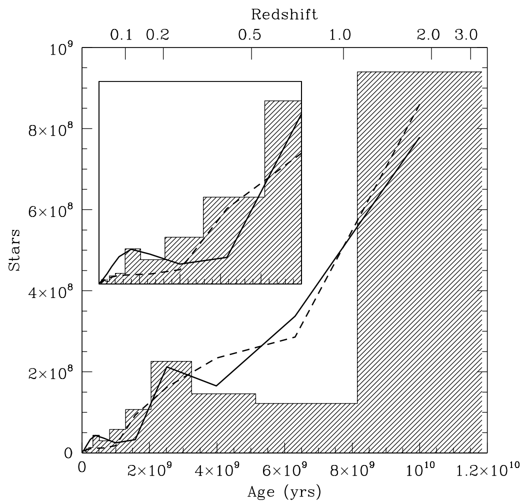

FIG. 4.— Comparison of the same tidally-triggered model as in Figure 2 (solid line; Model 2 in Table 1) and a model that is identical except the time since pericenter has been changed to 2.1 Gyr (dashed line; Model 4 in Table 1). The inset is an expanded version of the most recent 2.5 Gyr.

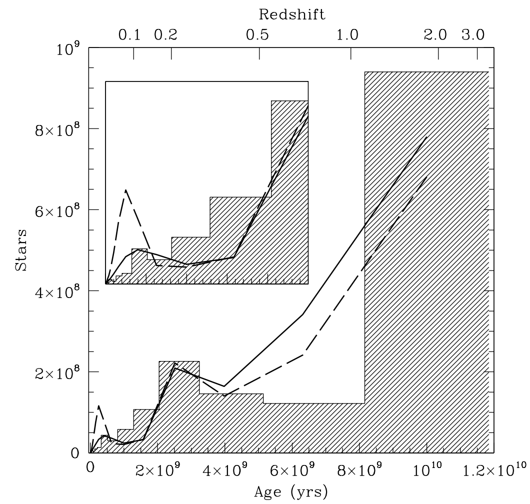

FIG. 5.— Comparison of a tidally-triggered model with $b = 2.4$ (solid line; Model 2 in Table 1), a tidally-triggered model with $b = 10$ (dashed line; Model 5 in Table 1), and the measured SAF (histogram). The inset is an expanded version of the most recent 2.5 Gyr.

3.1.4. *Tidal Triggering*

The crude, basic idea behind tidal triggering is that a rapid change in the tidal forces that a gas-rich galaxy experiences should disturb the kinematics of molecular clouds, hence increase the rate of cloud-cloud collisions, and thereby increase the star formation rate. Such models have been invoked over the previous several decades to qualitatively explain the range of phenomenon from relatively minor star formation enhancements (Larson & Tinsley 1978) to ultraluminous starburst galaxies (for review see Sanders & Mirabel (1996)). The details of how the increase in star formation scales with tidal force is unknown, but it presumably scales as some inverse power of the distance between the two galaxies. To model the dependence of the star formation rate on the separation between galaxies, r, we adopt the relationship that the SFR $\propto 1/r^b$. We have no external constraints on the value of b other than it must be $>$ 0 for star formation to increase with decreasing galaxy separation. As b increases the tidal effect becomes more impulsive and the form of the star formation enhancement approaches $\delta(t - t_{peri})$.

In Model 5 we explore the result of changing b from 2.4 to 10 (Figure 5). Even with the much more pronounced bursts, the bursts that occurred more than 4 Gyr ago are not discernible with the poorer temporal resolution available at those times. A change in b can be countered or enhanced with a change in the amplitude A of the TT mode (Figure 6, Models $6-7$). Large changes in A produce modest changes in the SAF, but dominate the calculation of the fraction of stars formed in the burst mode (for example, changing A from 10 to 1 reduces the fraction of stars formed in the TT mode from 58% to 12%).

3.1.5. *The Influence of the LMC?*

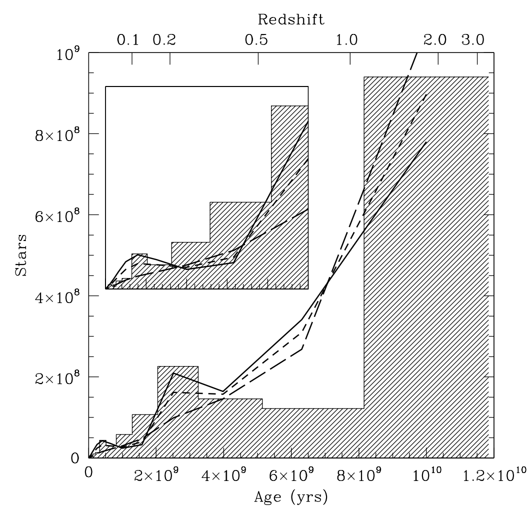

FIG. 6.— Comparison of a tidally-triggered model with $A = 1$ (long-dashed line; Model 7 in Table 1), a tidally-triggered model with $A = 10$ (short-dashed line; Model 6 in Table 1), a tidally-triggered model with $A = 100$ (solid line; Model 2 in Table 1), and the measured SAF (histogram). The inset is an expanded version of the most recent 2.5 Gyr.

One obvious ingredient that is missing from this model is the tidal triggering of star formation by the interaction between the LMC and SMC. It is much more difficult to model the orbit of the Clouds about each other, partly because the velocities are smaller so the observational uncertainties affect the solution to a greater degree and partly because the mass profiles of the two galaxies are not well known. It is therefore correspondingly more difficult to connect the SAF to the LMC-SMC orbital parameters. The SMC orbital models of Gardiner & Noguchi (1996); Yoshizawa & Noguchi (2003) find that the most recent LMC-SMC pericenter

passage is nearly coincident with the SMC-MW pericenter passage, thereby complicating the identification of the cause of that burst of star formation. According to the models, the tidal force exerted by the LMC was significantly larger at the most recent LMC-SMC pericenter than at any other time during the last 2 Gyr. Because the orbit of the SMC about the LMC is rather irregular (see Figure 3 of Gardiner & Noguchi (1996)) it is difficult to predict the times of any but the most recent close passage, but the models do not predict a close LMC pericenter passage at about 2 Gyr, where we find our older peak. Given the conclusions of Yoshizawa & Noguchi (2003) regarding the effect of the most recent LMC-SMC pericenter passage, one could conclude that a composite model is required where the LMC is responsible for the recent burst and the MW for the older burst. With our limited observational constraints we continue using our simple MW-only model, but future work must address the relative importance of the two interactions over the age of the SMC rather than just during the most recent passage.

There are several potential tests that could determine whether the MW or LMC close passages dominate the SFR. First, if the orbit of the LMC/SMC system about the MW was determined precisely to have a period of 1.5 Gyr, then we could exclude the MW as the dominant influence because of the SAF peak at $\sim$ 2.5 Gyr. As we discussed above, the current observational constraints are not sufficiently precise to exclude a period of 2.4 Gyr (necessary to reproduce the SAF). Second, if a comparable SAF for the LMC showed the same two bursts as seen in the SMC's SAF, then we could rule out the LMC as dominant influence because the SMC's tidal force should have a much smaller on the LMC than that of the LMC on the SMC. The available LMC data are currently inconclusive. Finally, if similar bursts are observed (or can be used to model the SAF) of other, isolated, Local Group galaxies, then we will know that the MW's tidal field is sufficient to drive global modes of star formation in its satellites.

There are three scenarios in which it might be acceptable to neglect the LMC-SMC interaction in this modeling. First, our model requires eccentric orbits, a changing tidal force, to produce bursts. Therefore, if the SMC-LMC orbit is fairly circular, more circular than found by Gardiner & Noguchi (1996), we would not expect tidal triggering. Second, if the orbit has a period that is smaller than the bin size (the resolution of our SAF), then we will not resolve the bursts caused by the interaction and the LMC-SMC TT mode will simply appear to cause an elevated constant star formation rate. Third, if the bursts are associated only with LMC/SMC pericenter passages that correspond to MW/SMC pericenter passages, as appears to have happened a few hundred million years ago, then our orbital model would have the correct behavior but our interpretation would be incorrect. Even though we cannot currently rule out the LMC as the dominant factor in triggering bursts, the correspondence of both SMC bursts to MW pericenter passages is strong circumstantial evidence for the importance of the MW passages on the SFR. Even if the LMC is eventually found to be the dominant source of triggering, an analysis examining the MW's influence could place upper limits on the importance of interactions. Resolving this ambiguity is critical to further progress in this type of analysis.

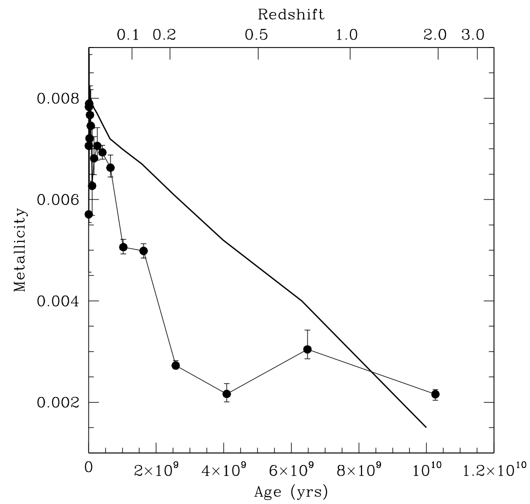

FIG. 7.— Comparison of the chemical enrichment history has derived from a tidally-triggered model of star formation (thick solid line; Model 2 in Table 1), and the derived chemical enrichment history from Harris & Zaritsky (2003) (thin solid line and data points). Once again the temporal position of the oldest point is somewhat ill-defined (see text).

3.2. *The Failings of Closed-Box Evolution and the Necessity for Infall*

Certain features in the SAF, namely the two peaks at $t < 4$ Gyr are reproduced quite well with simple closed-box models, but other features are not reproduced. The closed-box models have two fundamental deficiencies: (1) they do not reproduce the steep drop in the number of stars formed in the oldest and second oldest bin (alternatively described as the relatively quite period between 8 and 4 Gyr) and (2) they do not reproduce the flat, or perhaps even declining chemical enrichment history between 8 and 4 Gyr (Figure 7). Both of these shortcomings suggest that these models are not entirely satisfactory and that a possible solution may involve infall of low-metallicity gas into a galaxy that had significantly depleted its initial gas. The early exhaustion of gas would help explain the low SFR at 8 Gyr. The subsequent infall is necessary to dilute what would otherwise be a fairly metal rich gas (in a closed-box model the chemical abundance approaches the yield as the gas is exhausted) and provide the fuel necessary to explain the star formation at younger ages. Outflow might also be invoked, although it is difficult to understand why outflow might mitigate chemical enrichment at earlier times but not at later times unless the total mass of the galaxy has changed significantly in the last 8 Gyr.

In the spirit of continuing only with fairly simple models, we model infall as a single event of gas mass M_g at time t_{infall}. We now automate the exploration of parameter space by defining a χ^2 goodness-of-fit parameter, using the internal statistical uncertainties in the SAF, and identifying the minimum χ^2 value and likelihood contours using $\Delta\chi^2$. Table 2 presents the range of parameter space probed, the best fit values, and the 90%

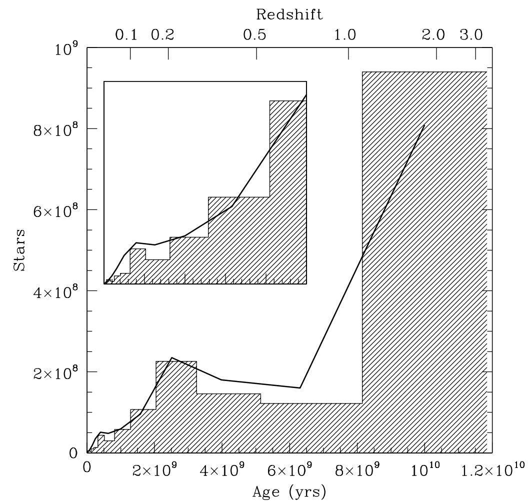

FIG. 8.— Comparison of the tidally-triggered model of star formation with infall that fits the SAF well (thick solid line; Model 8 in Table 1) and the measured star formation (histogram). The inset is an expanded version of the most recent 2.5 Gyr.

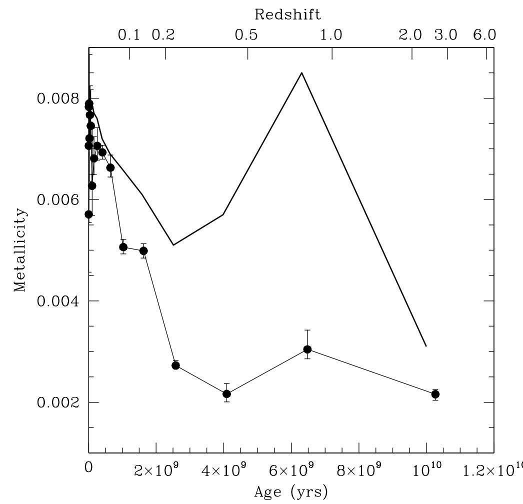

FIG. 9.— Comparison of the chemical enrichment history of the tidally-triggered model of star formation with infall that fits the SAF well (thick solid line; Model 8 in Table 1) and the derived chemical enrichment history from Harris & Zaritsky (2003) (thin solid line and data points).

confidence intervals. The parameter space was sampled coarsely resulting in some cases where the 90% interval includes only the best fit value. The fitted values in this Table should be viewed with some skepticism because none of the models is formally a good fit (the best-fit $\chi^2_\nu = 3.1$, which is significantly better than any model in Table 1, but still not ~ 1). The failure to statistically fit the data is in part due to the exclusion of systematic errors (see Harris & Zaritsky (2003)) and the oversimplification of the models. As an example of what we conclude is an underestimation of the SAF uncertainties we show in Figure 8 a model (model 8 in Table 1) that fits the SAF quite well, but is not within the acceptable ranges in Table 2.

There seems to be little improvement possible in reproducing the SAF, in particular because the lull in star formation at intermediate ages is now fit quite well. Unfortunately, the chemical enrichment history is not a good fit (Figure 9, corresponds to model 8). Although this model reproduces the see-saw pattern at old ages, the chemical abundance at those times is significantly higher in the models than what is observed. This discrepancy has three possible interpretations 1) the model is missing a key ingredient (possibly outflow of high metallicity gas in the early SMC), 2) the model is sufficiently sensitive to the parameter choice that another models within the confidence intervals for reproducing the SAF produces a much better fit to the age-metallicity relationship or 3) the observed chemical abundances are wrong (recall that although we believe them to be accurate because of the agreement with abundances published for individual clusters they are measured from broad band colors). We will ignore the latter possibility, although spectroscopic chemical abundances of a large sample of stars in the SMC would be of great benefit in testing our derived age-metallicity relationship for field SMC stars.

We focus on the second of the three possibilities, again because we are attempting to find the simplest model that is satisfactory. We do find a model in which the predicted abundance history is in better agreement with the data (Figure 10) at the expense of the agreement with the SAF (Figure 11). Given that we can reproduce the age-metallicity relation with one set of parameters and the star-formation history with a slightly different set in this simple model, we conclude that some combination of a slightly more complex model and the potential systematic uncertainties in both the star formation history and chemical abundance history ensure that a fully satisfactory solution exists within the framework advocated here. Given the uncertainties, the simplicity of the current model, and the limited number of observational constraints, we do not think it worthwhile to push the data further in addressing this issue or determining parameter values. Nevertheless, there are several conclusions that are not sensitive to whether one favors the model that is the best fit to the SAF or the one that is a good fit to the chemical enrichment history. All models that fit the SAF require concentrated bursts of star formation and a significant infall event (~ 0.5 gas mass fraction) at intermediate (4 – 5 Gyr) ages. The models with stronger bursts are better at reproducing the age-metallicity relationship while those we weaker bursts are better at reproducing the SAF. Unfortunately, with only one galaxy for comparison the models are underconstrained and therefore not necessarily unique.

3.3. *Other Local Group Systems*

Although there are tens of LG systems with which such an model could ultimately be tested, the data for most of these are not quite at the standard of that discussed here for the SMC. Published star formation histories do exist for most of the dwarf spheroidals and for selected fields in the LMC, but these are not done in a homogeneous manner with the latest analysis tools. An exception to this statement is the study of Dolphin (2002) that attempted to analyze a set of galaxies in a systematic way. Even

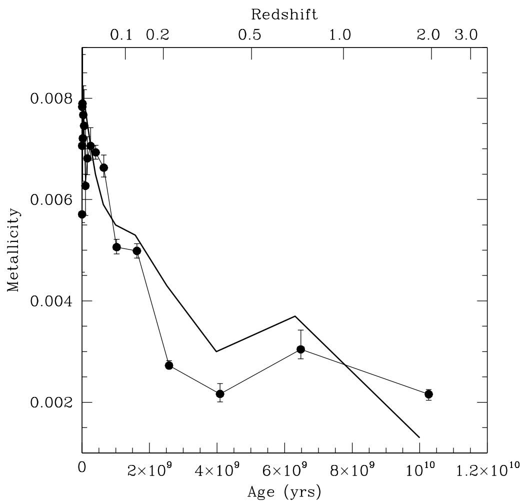

FIG. 10.— Comparison of the chemical enrichment history derived from a tidally-triggered model of star formation with infall (thick solid line; Model 9 in Table 1), and the derived chemical enrichment history from Harris & Zaritsky (2003) (thin solid line and data points). Note that this particular model generates a qualitatively good fit to the observed relationship.

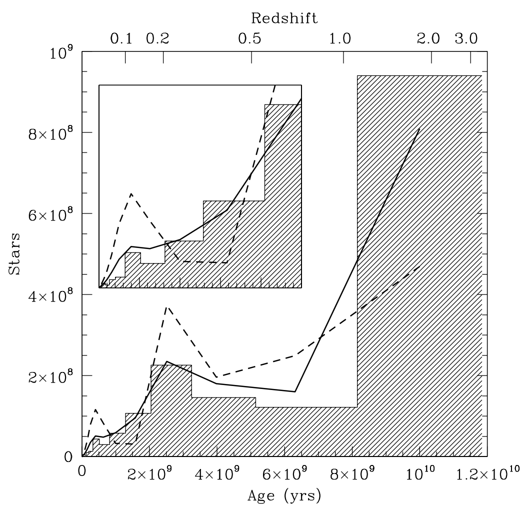

FIG. 11.— Comparison of the star formation history derived from a tidally-triggered model of star formation shown in Figure 10 (dashed line; Model 9 in Table 1), the tidally-triggered model with infall that fits the star formation history better (solid line; Model 8 in Table 1) and the SMC SAF (histogram).

so, that work includes the caveat that the SFHs are derived from HST observations, which do not include the entire galaxy. The presence of population gradients in even these simple systems (Harbeck et al. 2001) makes necessary larger area surveys to ensure a complete sampling of the SFH. Orbital solutions using precise proper motion measurements are still quite rare and available in the literature only for a few of the dwarf spheroidals. Therefore, although we will eventually be able to test the model on a large number of systems there are none currently that provide as good a set of constraints as the SMC.

4. SUMMARY

From our highly simplified modeling of the star formation history of the Small Magellanic Cloud we conclude the following:

1) The coincidence of two peaks in the SMC's stellar age function with the times of closest approach between SMC and MW, as determined from proper motion measurements and the integration of the orbit within the gravitationally potential of the Milky Way, suggest that a tidally-triggered mode of star formation is important in the SMC. The principal shortcoming of our modeling is the inability to model the effect of the LMC on the SMC due to our lack of detailed orbital constraints of the Magellanic Clouds about each other at times >2 Gyr. A composite model, where the more recent burst is due to the LMC, while the older is due to the MW, is consistent with the current data, but adds too much complexity to constrain further with the current data.

2) The elevation in the star formation rate is significant (> factor of 2) over the quiescent rate of star formation in the SMC. While the tidally triggered mode is measurable at recent times, it may contribute as few as 10% of all stars in the SMC or more than 50%. The uncertainty in this number is due to the low resolution in our star formation history, particularly at ages > 2.5 Gyr.

3) The preferred values of the exponent for the radial dependence of tidally-triggered mode of star formation suggest that tidally-triggered star formation can be accurately modeled as an impulsive effect on the star formation rate when the time resolution of the models is greater than about a hundred Myr.

4) The failure of the closed-box model to reproduce both the stellar age function and chemical abundances at intermediate ages in the SMC (4 − 8 Gyr) was resolved to a large degree with a single massive infall event that involved about 50% of the gas mass of the SMC infalling about 4 Gyr ago. We did not show that this is a unique solution to the problems posed by the closed-box model, but it is consistent with the differing distributions of younger and older stars in the SMC (Zaritsky et al. 2000).

5) Conclusions 2-4 depend only on the assumption that the enhancements observed in the stellar age function are due to periodic, tidally triggered star formation, but do not depend on whether those bursts are driven by the LMC, MW, or a combination of the two. If refinements in the orbital solutions of either the MW or LMC are able to exclude one or the other as driving influences of the observed bursts, then limits could be placed on the importance of tidal interactions on the star formation rate.

Future comparisons of such models should compare directly to the color-magnitude diagrams. It is therefore critically important for progress in this field to have a homogeneous, well-documented public database of photometry of Local Group galaxies with the ancillary data necessary to synthesize observed color-magnitude diagrams.

5. ACKNOWLEDGMENTS

DZ acknowledges financial support from National Science Foundation CAREER grant AST-9733111 and a fellowship from the David and Lucile Packard Foundation.

Table 1. Model Runs

Run No.	b	t_{peri}	P	Age	A	t_{infall}	f_{infall}	TT fraction	χ^2_ν
1	...	...	...	17.0	0.0	...	...	...	11.6
2	2.4	0.2	2.4	17.0	100.0	...	...	0.93	9.4
3	2.4	0.2	1.5	17.0	100.0	...	...	0.93	12.1
4	2.4	2.1	2.4	17.0	100.0	..	...	0.93	11.9
5	10.0	0.2	2.4	17.0	100.0	...	...	0.38	116.5
6	2.4	0.2	2.4	17.0	10.0	...	...	0.58	6.9
7	2.4	0.2	2.4	17.0	1.0	...	...	0.12	11.7
8	6.0	0.3	2.4	17.0	4.0	4.0	0.5	0.11	6.2
9	4.2	0.3	2.4	17.0	60.0	5.0	0.4	0.78	80.6

Table 2. Infall Model Best-Fit Parameters

Symbol	Range	Acceptable Range
A	0.2−10.0	1.2[1.0,1.6]
b	2.0−7.0	4.6[2.8,7.0)
t_{AGE} (Gyr)	14−17	17[17,17)
t_{infall} (Gyr)	3.0−7.0	4.0[4.0,4.0]
f_{infall}	0.3−0.6	0.4[0.5,0.5]

REFERENCES

Cole, S., Aragón-Salamanca, A., Frenk, C., Navarro, J. & Zepf, S. 1994, MNRAS, 310, 781

de Freitas Pacheco, J.A., Barbuy, B., & Idiart, T. 1998, å, 332, 19

Dolphin, A.E. 2002, MNRAS, 332, 91

Dopita, M. A., Ford, H. C., Lawrence, C. J., & Louise Webster, B. 1985, ApJ, 296, 390

Gardiner, L. T., & Noguchi, M., 1996, 278, 191

Gardiner, L. T., Sawa, T., & Fujimoto, M, 1994, MNRAS, 266, 567

Garnett, D.R. 2002, ApJ,581,1019

Hardy, R., Suntzeff, N.B., & Azzopardi, M. 1989, ApJ, 344, 210

Harris, J., & Zaritsky, D. 2001, ApJS, 136, 25

Harris, J., & Zaritsky, D. 2003, submitted to AJ

Flint, K. & Harris, J., 2003, in prep

Harbeck, D. et al. 2001, AJ, 122, 3092

Kauffmann G., White, S., & Guiderdoni, B. 1993, MNRAS, 310, 201

Kennicutt, R.C. 1989, ApJ, 344, 685

Kennicutt, R.C. 1998, ApJ, 498, 541

Kochanek, C.S. 1996, ApJ, 457, 228

Larson, R.B. & Tinsley, B.M. 1978, ApJ, 219, 46

Lin, D.N.C., Jones, B.F., & Klemola, A.R. 1995, ApJ, 439, 652

Madau, P., Pozzetti, L., & Dickinson, M. 1998, ApJ, 498, 106

Martin, C.L. 1999, ApJ, 513, 156

Mateo, M.L. 1998, ARA&A, 36, 435

Piatti, A.E., Santos, João, F.C., Clariá, J.J., Bica, E., Sarajedini, A., & Geisler, D. 2001, MNRAS, 325, 792

Quirk, W.J. 1972, ApJ, 176, L9

Sanders, D.B., and Mirabel, I.F. 1996, ARA&A, 34, 749

Schmidt, M. 1959, ApJ, 129, 243

Somerville, R.S., & Primack, J.R. 1999, MNRAS, 310, 1087

Spergel, D.N. et al. 2003, astro-ph/0302209

Spitzer, L. 1968, Diffuse Matter in Space (New York: Wiley)

Stanimirovic, S., Staveley-Smith, L., van der Hulst, J.M., Bontekoe, TJ.R., Kester, D.J.M., and Jones, P.A. 2000, MNRAS, 315, 791

Staveley-Smith, L., Sault, R.J., Hatzidimitriou, D., Kesteven, M.J., and McConnell, D. 1997, MNRAS, 289, 225

van der Marel, R. P., Alves, D. R., Hardy, E., and Suntzeff, N.B., 2002, AJ, 124, 2639

Vila-Costas, M.B., & Edmunds, M.G. 1992, MNRAS, 259, 121

Wilkinson, M. I., & Evans, N. W. 1999, MNRAS, 310, 645

Yoshizawa, A.M., & Noguchi, M. 2003, MNRAS, 339, 1135

Zaritsky, D., Olszewski, E., W., Schommer, R. A., Peterson, R.C., & Aaronson, M. 1989, ApJ, 345, 759

Zaritsky, D., Harris, J., Grebel, E.K., & Thompson, I.B. 2000, ApJ, 534, L53

Zaritsky, D., Harris, J., Thompson, I.B., Grebel, E.K., & Massey, P. 2002, AJ, 123, 855